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Indoor Air Quality, Humidity and Thermal Conditions: CIBSE Review of Recent Research and Guidance in Criteria and Solutions

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Abstract

This paper presents a summary of recent CIBSE guidance on health and wellbeing in buildings, including how to define indoor environmental criteria. In a rapidly-evolving field, it also summarises key areas of current research and development, how to evaluate such studies, and what to look out for when reviewing emerging products. The paper focuses on indoor air quality, thermal comfort and humidity, but many of its principles are valid for other aspects of indoor environments.

Overall, CIBSE guidance advocates for source control, the precautionary principle, and monitoring of building performance in order to avoid unintended consequences.

Key themes of active research, with potential for significant improvements to health and comfort, include:

- improving our understanding of conditions best suited to a range of populations (e.g. the elderly, children);
- assessing the impact of, and designing for, exposure to a range of environmental stressors. This would be an evolution from current guidelines which tend to respond to one factor alone (e.g. responding to combined excessive heat and noise, rather than to one or the other);
- building our knowledge of impacts and solutions in the housing retrofit sector, considering jointly the effects on energy consumption, comfort, indoor air quality and humidity.

Keywords

Comfort; health; building performance; indoor environmental conditions; air quality; overheating; humidity.

1. Introduction

The past decade has seen significant advances in our understanding of how environmental factors such as light and air quality affect our health and wellbeing. At the same time, life expectancy is increasing around the world [1]; while this is clearly to be welcomed, it also increases pressures on care and healthcare systems due to ageing populations [2]. In many countries this is accompanied by a rise in non-communicable diseases (NCDs), often related to lifestyles and our physical, social and economic environments [3], [4], and by a rise in health inequalities: in the UK, people in areas of lower incomes live on average nine years less, and spend 18 years more in poor health [5], [6]. Worldwide, our physical environments are also undergoing huge changes, from the new dominance of urban living to the ubiquity of electro-magnetic fields from electricity and communications networks. There is therefore increasing attention from health professionals and policy-makers on preventive public health approaches.

In addition, there is a growing realisation of the impact of indoor environments in workplaces, as we spend most of our time indoors, and an increased attention to productivity and well-being, in order to improve competitiveness and attract and retain valued employees [7].

In response to these trends, CIBSE has been doing substantial work to update its guidance on healthy environments, with the publication of revised TM40 – *Health and Wellbeing in Building Services* – in late 2019. This article presents a summary of key updates including guidance on what constitutes good indoor environments, key areas of knowledge gaps, active research and technical developments. It focuses on indoor air quality, humidity and thermal conditions. TM40 also advocates a similar approach to other environmental factors such as light and acoustics, i.e.:

- Defining clear health-based performance criteria;
- Assessing the site's characteristics to inform the design strategy;
- Applying the precautionary principle and source control approaches first;
- Monitoring and assessing performance in use, sharing lessons and striving for continuous improvement.

2. Defining environmental criteria for health, comfort and cognitive performance: Proposed approach

Defining criteria for health

An important part of CIBSE's work has been to define environmental criteria for health, comfort and cognitive performance. This has been done in collaboration with health experts, including Public Health England, and based on a review of the scientific and regulatory background. The aim is not to turn built environment professionals into health experts, but to equip them with a basic understanding of the effects of environments, of core principles such as source control and the precautionary principle, and of the background and caveats behind recommended guidelines.

The new recommended guidelines have been derived from a systematic review of existing health-based guidelines, regulations (focusing on the UK), and best practice guidance from established industry sources. The recommendations are expressed in terms of building performance outcomes for each environmental factor (light, humidity, thermal conditions etc), using a number of metrics: for example, pollutant levels in the case of air quality, and recommended ranges and maximum exceedance levels of operative temperature in the case of thermal conditions. These recommendations may be used as targets, for example in new buildings, substantial fit-outs and refurbishments, or as benchmarks in existing buildings to define priorities and short to longer-term improvement programmes.

For health purposes, as a very minimum it is recommended to meet regulatory requirements and recognised health-based guidelines including those from the World Health Organisation (WHO) (or its recognised agencies, as in case of electromagnetic fields) and Public Health England. This is broadly consistent with trends emerging from other recent guidance documents such as BS ISO 17772:2018, the revised BB101, 2018 [8], and BS EN 16798-1:2019.

What the new approach means, compared to regulatory minima

In many cases in the UK and EU, regulations incorporate and are more onerous than WHO guidelines; notable exceptions are indoor air quality and overheating, where there are currently no comprehensive regulations. Professionals are therefore strongly advised to refer to WHO guidelines for air quality, and best practice industry guidance for thermal comfort, including CIBSE TM52 (2013) for non-domestic buildings and CIBSE TM59 (2017) for dwellings – see Figure 1, next page.

In some areas such as air quality, the approach proposed in CIBSE TM40 to define indoor performance criteria represents a significant shift from current practice: the term "air quality" is often used by built environment professionals when actually referring to design measures (e.g. ventilation rates), indicators (e.g. Total Volatile Organic Compounds – TVOCs) or occupant perceptions (e.g. smells, complaints of "stuffiness") – see Figure 2, next page. Ventilation and indicators without consideration of potential indoor and outdoor pollutant sources are no guarantee of good indoor air quality.

Similarly, while occupant feedback is useful to gauge comfort and satisfaction, it does not guarantee health-based outcomes, a stark example being carbon monoxide which can be lethal but is not detected by humans. It is also recommended to avoid the term "sick building syndrome", which covers a range of possible symptoms and causes, rather than being specific about what the problem (and therefore the solution) may be [9].

Defining criteria for comfort

For comfort purposes, current good practice recommendations from CIBSE have been found to be largely valid, at least in most environments with healthy populations, which is typically where recommendations were established in the first place. In these environments, most occurrences of discomfort reported by users occur in situations when the internal environment differs from current good practice guidelines. This stresses the importance of good design and operation, and of user choice and

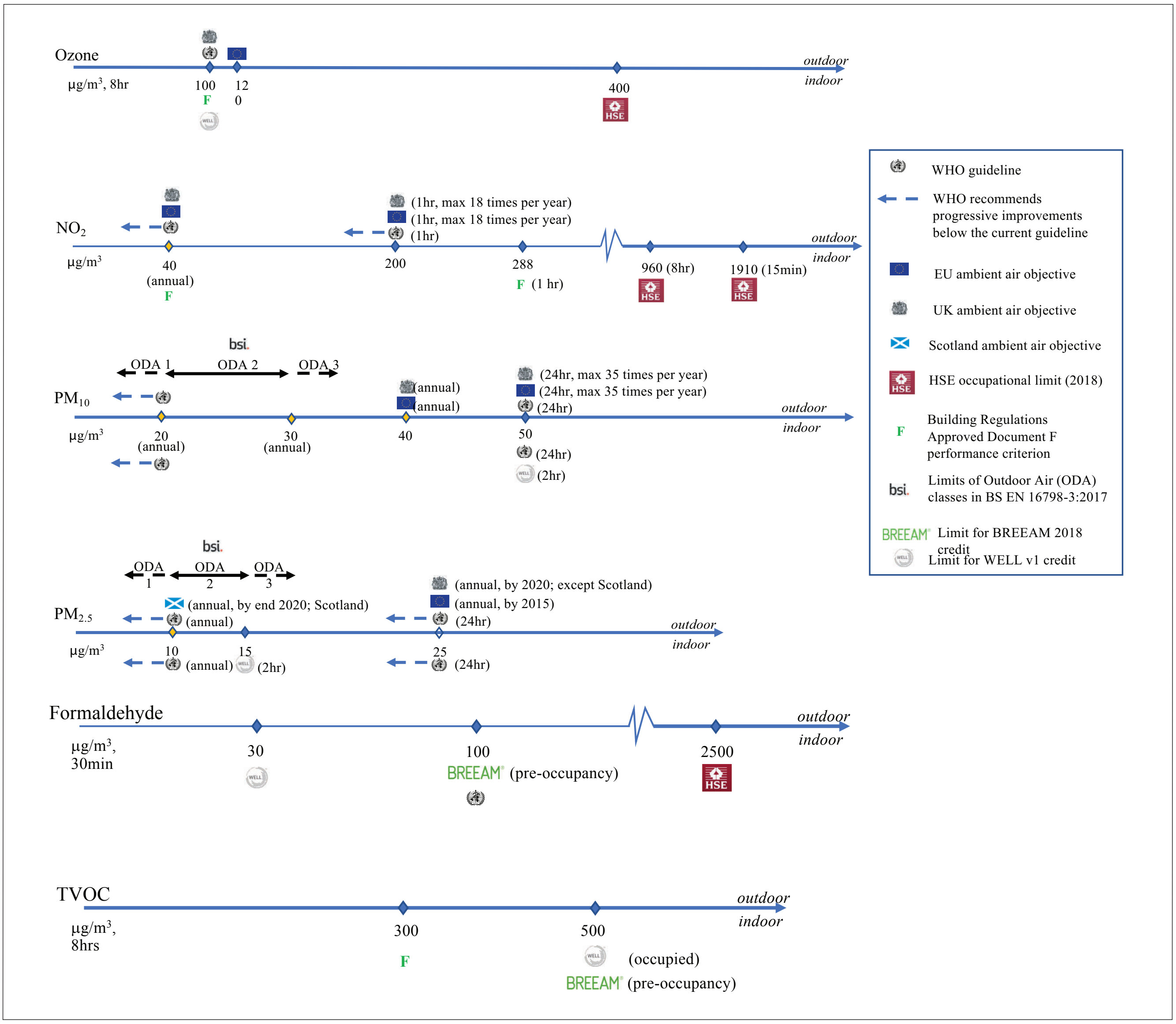

Figure 1. Illustration of guidelines and regulations for a selection of air pollutants: for many pollutants, current UK regulations only apply to occupational exposure, or only cover outdoor air rather than indoor environments. In these cases the current CIBSE recommendation is to refer to WHO guidelines for indoor air quality.

control over their environment, to account for individual sensitivities and preferences. This is not a new recommendation, and a large body of evidence from decades of post-occupancy evaluation supports it [10], [11], [12].

3. Defining environmental criteria for health, comfort and cognitive performance: complexities and caveats

It is important for practitioners to understand that the approach described in the previous section, while useful as a practical starting point, is constrained by important remaining gaps in our understanding of how environmental factors affect us. These gaps broadly apply to three areas:

- How individual environmental factors affect health, comfort, and cognitive performance;

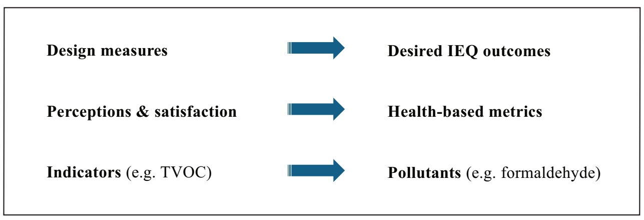

Figure 2. Adopting a more specific approach to defining indoor environmental performance.

- How a combination of factors affects us: guidelines are typically based on exposure to single factors rather than on combined exposure to several factors, which in real life is very likely; for example, exposure to air pollution and noise in locations near busy roads, or the effects of cold, damp and inadequate ventilation in low-quality housing;
- How to cater for a wide range of physiologies, medical conditions, preferences etc.

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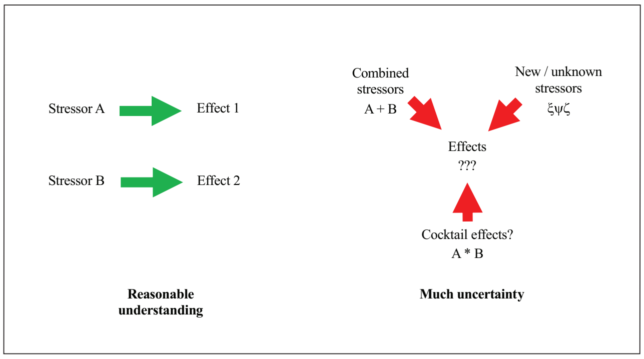

Figure 3: Simple illustration of some of the gaps in our understanding of the effects of environmental factors.

Some of these knowledge gaps may be filled in the future. For others, their complexity likely means that we will need to rely on a precautionary approach and on knowledge accumulated over time on the range of environmental conditions and design measures which do not show detrimental effects.

3.1 Dealing with varied populations

Current guidelines are necessarily simplified to apply to most cases for healthy adult populations. Guidance for specific parts of the populations which have different sensitivities, such as children, pregnant women, the elderly, or people with existing medical conditions is in general much less established. In comfort terms, guidance is often weighted towards men, due to the fact that many guidelines were initially developed on offices in the 1970s. This may have implications on occupant comfort and satisfaction now. For example, a review of building use studies over 47 non-domestic buildings found that that women had significantly more negative perceptions of air quality and of winter conditions[13]; more research attention is now being placed to better understand comfort for some populations, in particular the elderly[14].

The complexity of catering to a range of populations is illustrated by allergies, asthma and sensitivities, an area where our understanding of cause and effect is still relatively limited: in some cases, individuals exhibiting strong responses to exposure to one substance may be seen as "canaries in the coal mine" i.e. they exhibit a more immediate, obvious and acute reaction to something that affects us all but to lesser degrees. In others, such as food allergies, the reactions are specific to these individuals, whether due to medical conditions or other factors such as medication or drug use, and the rest of the population does not risk harmful effects from exposure. Finally, in other cases individuals are convinced that exposure to a particular factor is causing them harm, and they suffer from very real symptoms, but the current science does not support a causal link to the factor

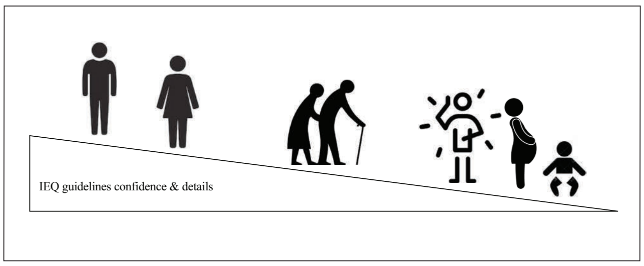

Figure 4: Simplified representation of the current state of knowledge and certainty in how IEQ guidelines apply to a range of populations.

being blamed. This is the case for example with "electro-sensitivity", or perceived hyper-sensitivity to electro-magnetic fields (EMFs), where available meta-analyses and double-blind experiments do not support a link between such symptoms and short- or long-term exposure to EMFs[15], [16].

Some evidence suggests there may be broader causes, such as personal circumstances or the acceptance (or not) of new technologies, particularly when these technologies are perceived as imposed without people's control[17]. This means that built environment professionals sometimes need to show an understanding of people's very real distress, while being able to support their design proposals with the best available knowledge at the time.

3.2 Indoor air quality

Broad guidelines for indoor air quality (IAQ) are now available as a starting point. In England for example, the National Institute for Care Excellence (NICE) has recently published draft ones on IAQ in homes, for consultation[18]. There are, however, still gaps in a number of areas, such as:

- Cumulative effects of exposure to multiple pollutants, including a combination of particulates, NOx and volatile organic compounds from furniture, finishes and consumer products;
- Mixture effects between these multiple pollutants ("cocktails") which may reduce or dampen the effect of individual pollutants;
- Emerging pollutants, whether they are new or not much studied previously. One example is pollutants emitted by consumer products such as air fresheners and cleaning or personal care products. Another is fire-retardant materials in furniture, furnishings etc, which are slowly released in our environments. These are often subject to little testing other than on their capacity to delay the onset and spread of fire. Some, such as brominated fire retardants, are known to have detrimental effects and are subject to some limits in parts of the world. There are also concerns that some may increase the risk to health during a fire by releasing toxic fumes, with effects not only on building occupants but also on firefighter populations[19].

3.3 Thermal conditions

There is currently a lack of health-based guidelines on temperatures, especially in terms of upper thresholds and applying to different populations, including the elderly or very young, vulnerable etc. The CIBSE guidelines instead build on decades of empirical research on acceptable comfortable ranges. Research on the impact of thermal conditions on health and comfort sometimes leads to different or even contradictory thresholds and guidelines. Some of the themes being explored are:

- While guidance on temperatures often focuses on experienced thermal comfort, exposure to lower temperatures may have benefits for our metabolism, possibly even more if exposure is for short periods, which prevents acclimatisation[20],[21];
- Current criteria tend to focus on "average" conditions. However, as for all health effects, the notion of exposure is important[22] i.e. how long someone is exposed to a certain temperature, how often, and the extent of the departure from "neutral". CIBSE TM52 already includes a criterion for severity of overheating in

terms of temperature and duration, but it does not consider, for example, whether the limits are breached consecutively or whether respite is possible by cooler days in between;

- Beyond exposure and health effects, there is also a growing argument that variations, both temporal and spatial, can in themselves contribute to pleasant and even "delightful" environments. This applies to thermal conditions as well as, more broadly, variations in physical environment factors[23], [21], [24];
- A better understanding may be required of the potential long-term effects of adaptation approaches, particularly for vulnerable populations or children[25], who may not necessarily have a choice or be able to express feedback;

3.4 Humidity and microbial contaminants

There are no WHO guidelines on levels of mould, microbial contaminants and allergens such as dust mites. Such guidelines would be very complex to establish and are unlikely to emerge in the near future[26]. Instead, CIBSE guidance follows recommendations by WHO and uses a recommended range of relative humidity (40-60% in domestic environments and mechanical cooled, and 40-70% elsewhere) and surface temperatures, coupled with ventilation, based on empirical evidence of environments that support or hinder comfort, mould growth, fabric degradation and other direct and indirect effects of humidity.

3.5 Impacts on cognitive performance

Beyond health and comfort, professionals also aspire to define and provide the right environmental factors to support our cognitive performance, notably in support of productivity in offices. This relies on being able to assess productivity, a complex exercise in itself and a very active area of research. Studies on the impact of environmental factors on our performance vary greatly in quality, and often simply reinforce existing guidance, because the improvements in performance are shown by comparison with poor-quality environments. Figure 5 illustrates recommendations on how to approach these studies.

One of the main areas of research in this field is on what should be the limits to internal CO_2 levels, and the potential for improvements to cognitive performance through lowering them below current good practice recommendations[27]. Traditionally, at levels typically found in buildings, internal CO_2 has been seen as an indicator of ventilation effectiveness rather than a pollutant in itself. There is no WHO guideline limit on it, and UK regulations only have occupational exposure limits (COSHHH – WEL) in order to prevent high CO_2 levels leading to headaches, dizziness, confusion and loss of consciousness

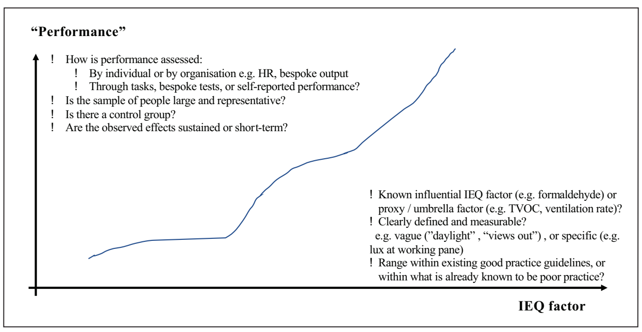

Figure 5. Studies on indoor environmental factors vs cognitive performance: Tips on what to look out for .

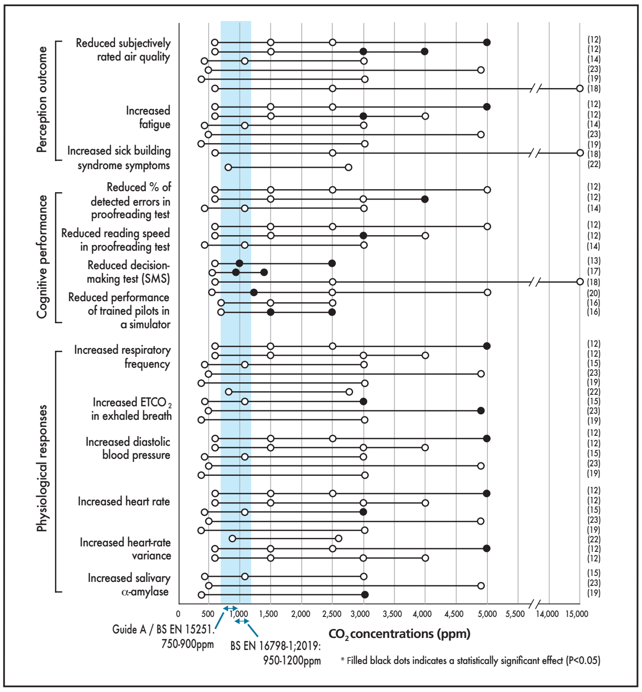

Figure 6: Key results of research on whether CO_2 concentrations affect human perceptions, health and cognitive performance[31], overlaid with recommended levels in CIBSE Guide A (based on BS EN 15251) and in BS 16798-1:2019 (which replaces BS EN 15251), assuming "high" and "medium" quality classes and outdoor CO_2 levels of 400ppm

(5,000ppm for an 8-hour exposure and 15,000ppm for a 15-min exposure).

Recent years have, however, seen a small number of controlled experiments where CO_2 levels were varied independently from other factors. Most (but not all) of these tests seemed to indicate that CO_2 may have an effect on its own on cognitive performance, and at levels lower than assumed in the past[28], [29]. However, it should be noted that these are still relatively isolated studies, and the most marked and unequivocal improvements occur well above 1,000ppm. Reviews[30], [31] have reached similar conclusions – CO_2 does seem to have an effect on its own, rather than simply being a proxy for ventilation effectiveness, but the evidence is still somewhat inconsistent. Apart from decision-making tests, the large majority of statistically-significant effects are shown well above the recommended range in current industry guidance, as illustrated in Figure 6.

4. R&D in solutions for indoor environments

The above relates to research on what constitutes the right indoor environmental environments to support our health, comfort and cognitive performance. There is also much R&D in *how* to achieve these environments.

The following important topics are not covered here – indoor environmental monitoring, procedures and equipment; the impact of plants; and urban climates. All three are topics of active research, including by CIBSE. Research reviews and guidance are expected to be produced in the future.

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4.1 Indoor air quality

Many products are being researched and developed to improve indoor air quality, often focusing on how to "remove" pollutants. The first thing to note is that, as a core principle, source control should be applied in priority, preventing the generation and introduction of pollutants in a space, before attempting to remove them. Following this, known and tested solutions such as filters can be applied (whether established and well-proven, such as particle filters, or more niche solutions starting to be applied to broader contexts, such as carbon filters targeting NOx or VOCs). Notwithstanding this, this section provides an overview of some of the "removal" solutions being researched.

Some, such as traditional building materials, have been in use for a number of years and the main uncertainty is about the claims being made. There is much more uncertainty and risk of unintended consequences with new products, or with well-intentioned phase-outs and substitutions. For example, some concerns have been expressed that the use of low-VOC paints may lead to increased risks of bacteria and mould growth, or to the use of biocides which themselves have adverse effects[17].

The following approach is recommended when examining potential new solutions:

- Are the product's claimed benefits based on real-world experiments? If so, how were the multiple parameters of a real-world environment controlled? In the case of laboratory studies, how representative are they of real-life situations?
- Are the effects expected and proven in the long-term?
- The proposed solution may have proven positive impacts on specific target pollutants, but have possible reactions with other components in the air been considered?
- What is the required extent of application of the system or product (e.g. in exposed area per room volume), and is this realistic?
- If a pollutant is claimed to be "removed", by which process is this? In the case of absorption (or other "fixation" process), is it proven over time, taking account of possible re-release? In the case of decomposition, what are the by-products and their effects?
- Are the claims based on independent research?
- Is data available from existing case studies?

The following examples illustrate the importance of these questions.

Photocatalytic removal using titanium dioxide – This has been studied for many years to address a range of pollutants, with potential indoor and outdoor applications including paints or covering on walls and internal duct surfaces. A recent independent comprehensive review[32] on its potential to reduce NOx levels concluded there is little evidence of impact in outdoor applications, or the impact would be very small and require very large exposed areas. It does seem to reduce NOx levels when applied indoors, but there remains much uncertainty on other possible consequences e.g. other hazardous pollutants such as ozone may be generated from the photocatalytic decomposition of NOx or of other air pollutants.

VOC-reducing materials – A number of claims are being made about materials which may help reduce indoor VOC levels, typically either by absorbing or decomposing them. One example is wool, which has been shown to have VOC absorbent properties. The extent would depend on the type of wool, and the air would need to be in contact with the wool, which implies applications for furniture and flooring/wall coverings rather than insulation[33]. The body of evidence is not yet substantial, and the effect may be small, but long-standing historic applications mean there is little risk of unintended consequence.

Other new products claim to decompose VOCs into "inert products" which would then be either released into the air or bound to the product in question. However, there is little public data on the mechanisms and by-products, and claims should be examined carefully.

Air ionisation – It has been suggested that the ion balance of the air is an important factor in human comfort, with negative ions tending to produce sensations of freshness and well-being, and positive ions causing headache, nausea and general malaise. There is no clear evidence on this. From a medical health point of view (rather than feelings of comfort and wellbeing), a recent review concluded that exposure to negative or positive air ions does not appear to play an appreciable role in respiratory function, with no clear evidence to link exposure to negative air ions with benefits in respiratory function or asthmatic symptom alleviation, nor to link exposure to positive air ions with a significant detrimental effect on respiratory measures[34].

4.2 Thermal comfort

There have been a number of advances in the past few years in how practitioners can assess and respond to overheating risk. The tools available have evolved significantly and now cover a range of contexts and levels of complexity, such as:

- steady-state methods, such as the Passivhaus method (PHPP) or BRE's Home Quality Mark summer temperature tool, are still constrained by their very nature (typically using monthly whole-dwelling average air temperatures) but have evolved to take account of feedback from completed projects and from more complex methods;
- dynamic modelling is more widely used and has benefited from the framework provided by CIBSE TM59 in residential applications;
- a recent addition to the range of tools available is the guidance produced by the Good Homes Alliance[35]. This provides a simple risk assessment meant for the early stages of design. While the range of factors contributing to overheating risk has been well known for a while, especially thanks to the work of the Zero Carbon Hub, until recently this was typically provided as a long list. The Good Home Alliance guidance attempts to address this by drawing the most important factors (glazing, site context, ventilation strategy and design of the openings) for designers to focus on at the early stages;
- the need for simple and clear guidance based on property type and site context to inform early design decisions was also reinforced by the recently published research into overheating in new homes by MHCLG (https://www.gov.uk/government/publications/research-into-overheating-in-new-homes).

It will be important for these tools to keep evolving and learning from each other and from real-life feedback, as all contain necessary assumptions and simplifications which need to be tested and balanced. See for example recent investigations into modelling vs monitored temperatures in the recent BSERT Special Issue on overheating[36].

Design – it is possible that the evolution of some design approaches will help reduce the risk of overheating risk to a certain extent. For example, we may improve our understanding of where and how to exploit thermal mass in dwellings. While conventionally it has been beneficial in traditional, often rural settings, there are concerns about its use in urban settings where the urban heat island effect reduces the drop in night-time outside temperature and where noise may prevent occupants from opening their windows and cooling down the thermal mass. Furthermore, post-occupancy evaluation often shows that UK occupants are unfamiliar with the concept and, as a result, do not operate it usefully. This may evolve over time with more research, better user education, and technical improvements such as quieter mechanical ventilation systems, acoustically-attenuated openings, and more attention to the location of thermal mass (e.g. away from bedrooms, where it would release heat at night but maybe in other rooms and/or on the outer face of walls).

Product development may also help – Summer bypass functions are currently not always provided on mechanical ventilation with heat recovery (MVHR) units and, when they are, show a wide variety of approaches, some of them likely to compound overheating risk (e.g. reducing the ventilation rate). Ceiling fans may become more commonly available and quieter, ideally used in combination with higher floor-to-ceiling heights. It would also be useful to develop sensors or control strategies that better reflect the conditions experienced by occupants, i.e. at least the operative temperature, rather being based on air temperature only. In highly-glazed buildings this is a known cause of discrepancy between "satisfactory BMS readings" and feedback from occupants.

However, the above are likely only to play a small part in reducing overheating risk. The real benefits will occur by improving our practices of collaboration between clients and engineers to implement passive design strategies from the very early design stages, including site layout and façade design. These are where the most effective measures can be implemented to limit the risk of excessive solar gains, and to ensure heat dissipation through effective ventilation. This should come along with the provision of choice for users, whether it is over temperature, air movement or seating area.

Management – Beyond the design and operation of the buildings themselves, the negative effects of overheating can also be reduced through management, both at the building level (e.g. the relaxation of dress code, as seen during the recent heatwaves in a number of British institutions such as the Lords cricket ground in England and schools in Wales) and at a wider public health policy level. Public Health England estimates that a proportion of excessive summer deaths are preventable through precautions such as awareness and education campaigns. Examples include encouraging regular hydration and social networks around vulnerable populations, and the principles of individual and community preparedness as published in the *Heatwave Plan*[37] which need to be widely disseminated. Recent figures give reason for optimism in this area. While the 2003 and 2006 heatwaves are estimated to have caused over 2,000 excessive deaths in England[38], [39], the 2018 heatwave is associated with less than half the number of excessive deaths, below 900, despite having similar temperatures to the 2003 summer. This improvement may, at least partly, be attributed to the presence of a public heatwave planning[39].

4.3 Housing retrofit

Energy efficiency improvements to the existing housing stock have been recommended for a number of years for energy savings and carbon reduction purposes. In addition, housing conditions such as cold and damp are linked to negative health outcomes, particularly for people in fuel poverty[40], [41]. Energy efficient homes in Europe, whether new or retrofitted, are on average linked to better health[42].

Home energy efficiency improvements are therefore recommended by recent EU EPBD amendments[43] and by public health professionals[40], and regulations are increasingly put in place to this effect. In the UK these include the Minimum Energy Efficiency Standards for rented properties in England and Wales[44], the government's statutory target that all homes in fuel poverty should have an Energy Performance Certificate (EPC) of C by 2030, and its ambition that as many of the other homes as possible should achieve it by 2035[45].

Reviews of energy efficiency improvements to UK homes have usually found small but significant positive impacts on health, particularly for households on low incomes and on children, the elderly and people in poor health. The benefits can be wide-ranging but are particularly noticeable on specific medical conditions, especially respiratory symptoms and mental health[46], [47], [48], as well as general comfort and living conditions[49]. There is, however, also evidence of potential unintended adverse impacts, chiefly from insufficient ventilation rates leading to high humidity levels promoting mould growth and HDM[50], [51], high levels of indoor pollutants[51] and increased overheating risk[52], [53], [54]. In some cases there is also a risk of fabric degradation, particularly with solid wall insulation programmes which are poorly assessed or implemented[53].

As retrofit programmes are expected to increase in order for the UK (and Ireland) to meet its carbon reduction targets, it will be crucial to avoid unintended consequences on the health and comfort of occupants. The recently-released PAS 2035 provides a first step to whole-house retrofit approaches, and work is already starting on its future revision. Research shows that achieving energy efficiency savings as well as health benefits is possible, but relies on careful consideration and a holistic balance of measures including the following[42],[50],[53],[55], [56]:

- Adequate ventilation rates (energy savings would still be achievable through the overall retrofit);
- Consideration of the need for additional shading and night-time ventilation to limit overheating risk;
- Source control to limit indoor pollutants such as combustion by-products and harmful VOCs;
- Careful assessment of the existing fabric, heat and moisture flows, and proposed technical solutions, including risk of thermal bridging and condensation;
- Good workmanship and quality control procedures;

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- Training of occupants post-refurbishment, e.g. regular opening of windows, operation and maintenance of mechanical ventilation systems.

In order to address current knowledge gaps and deliver continuous improvements to building performance and to our understanding of effects on occupants' health and comfort, the impacts of retrofit programmes should be monitored more systematically:

- *Joint analysis of impacts on energy consumption, comfort and health:* pre- and post-retrofit studies often focus on a particular aspect in isolation, for example investigating changes to health outcomes, but not assessing whether actual energy savings were delivered. As already detailed, retrofit works can impact a number of inter-related factors, including internal temperatures, relative humidity, indoor air quality, fabric degradation and energy consumption. These outcomes should therefore all be examined and reported on jointly. For example, in some cases energy savings may be limited (or non-existent) as heating behaviours change (often described as the rebound effect), but this may in itself have positive effects on thermal comfort and health, particularly in low-income households.
- *Monitoring actual outcomes:* The impacts in terms of energy savings, the indoor environment or health and wellbeing are often modelled or assessed using proxies (e.g. temperature, VOC levels) rather than being based on measured evidence of energy and health outcomes;
- *Data on long-term impacts:* currently, the majority of studies focus on the first 12 months after improvement works [46], which may not capture long-term impacts on health outcomes or on fabric degradation.

5. Conclusion

There are still significant areas where our understanding of how to define and deliver indoor environmental conditions could improve our health, comfort and possibly our cognitive performance. Key areas include improving our understanding of conditions best suited to a range of populations (e.g. the elderly, children); assessing the impact of and designing for exposure to a range of environmental stressors, as an evolution from current guidelines which tend to respond to one factor alone (e.g. responding to combined excessive heat and noise); and building our knowledge of impacts and solutions in the housing retrofit sector, considering jointly the effects on energy consumption, comfort, indoor air quality and humidity.

An important conclusion from this evolving field is to follow the precautionary principle and apply source control, since some effects on health many only manifest themselves in the long-term, as in the case of asbestos and lead paint. This does not prevent innovation, but requires a cautious review of claims, possible effects, and monitoring and evaluation to keep new uses under review.

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